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Li et al.

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- (54) **TUNABLE REFERENCE CIRCUIT**
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- (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 832 days.

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(57) **ABSTRACT**

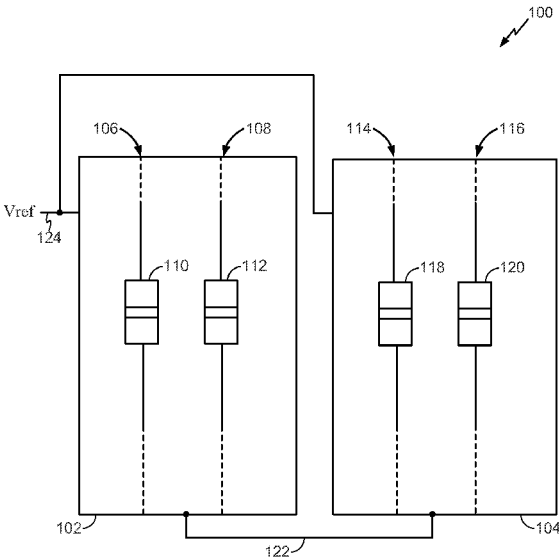
A circuit includes a first reference pair that includes a first path and a second path. The first path includes a first magnetic tunnel junction (MTJ) element, and the second path includes a second MTJ element. The circuit further includes a second reference pair that includes a third path and a fourth path. The third path includes a third MTJ element, and the fourth path includes a fourth MTJ element. The first reference pair and the second reference pair are tied together in parallel. A reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements. The reference resistance of the circuit is adjustable by adjusting a resistance of one of the MTJ elements.

36 Claims, 8 Drawing Sheets

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- (58) **Field of Classification Search**
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See application file for complete search history.

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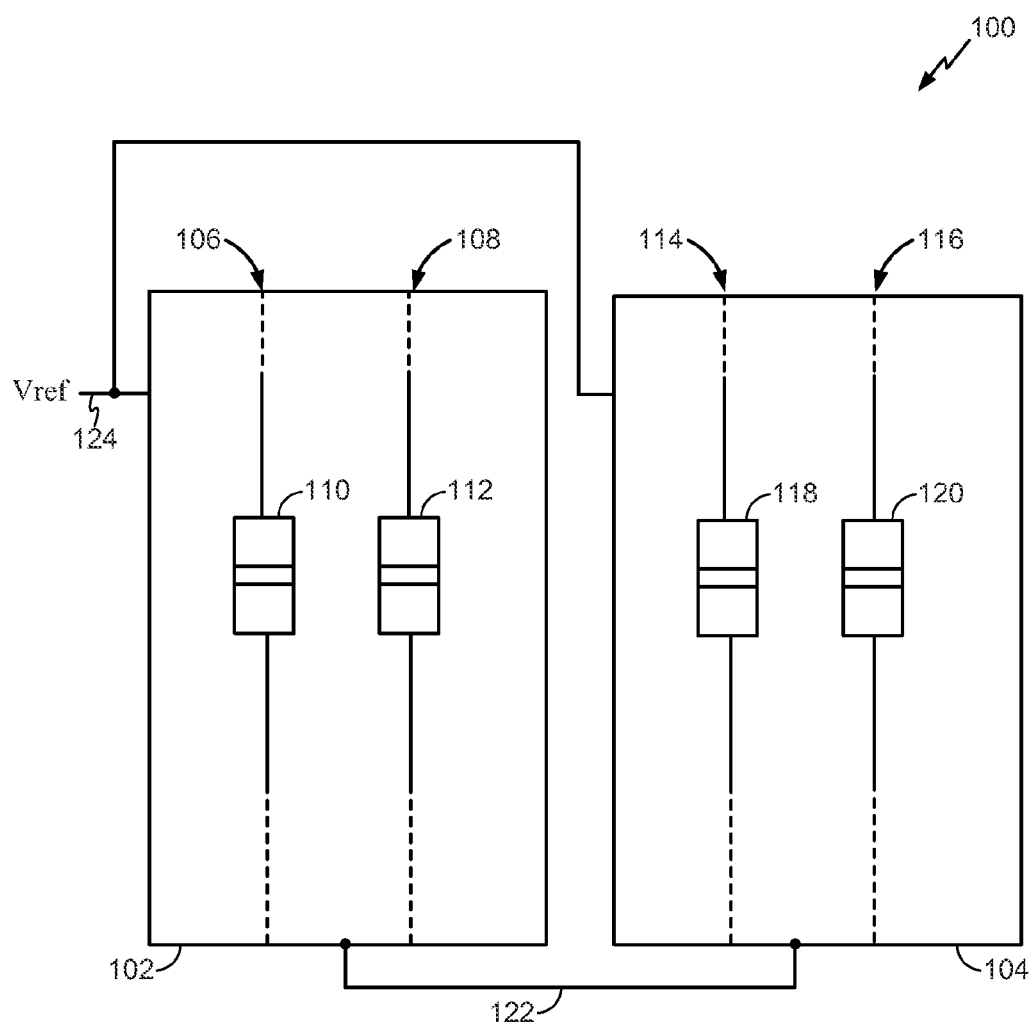
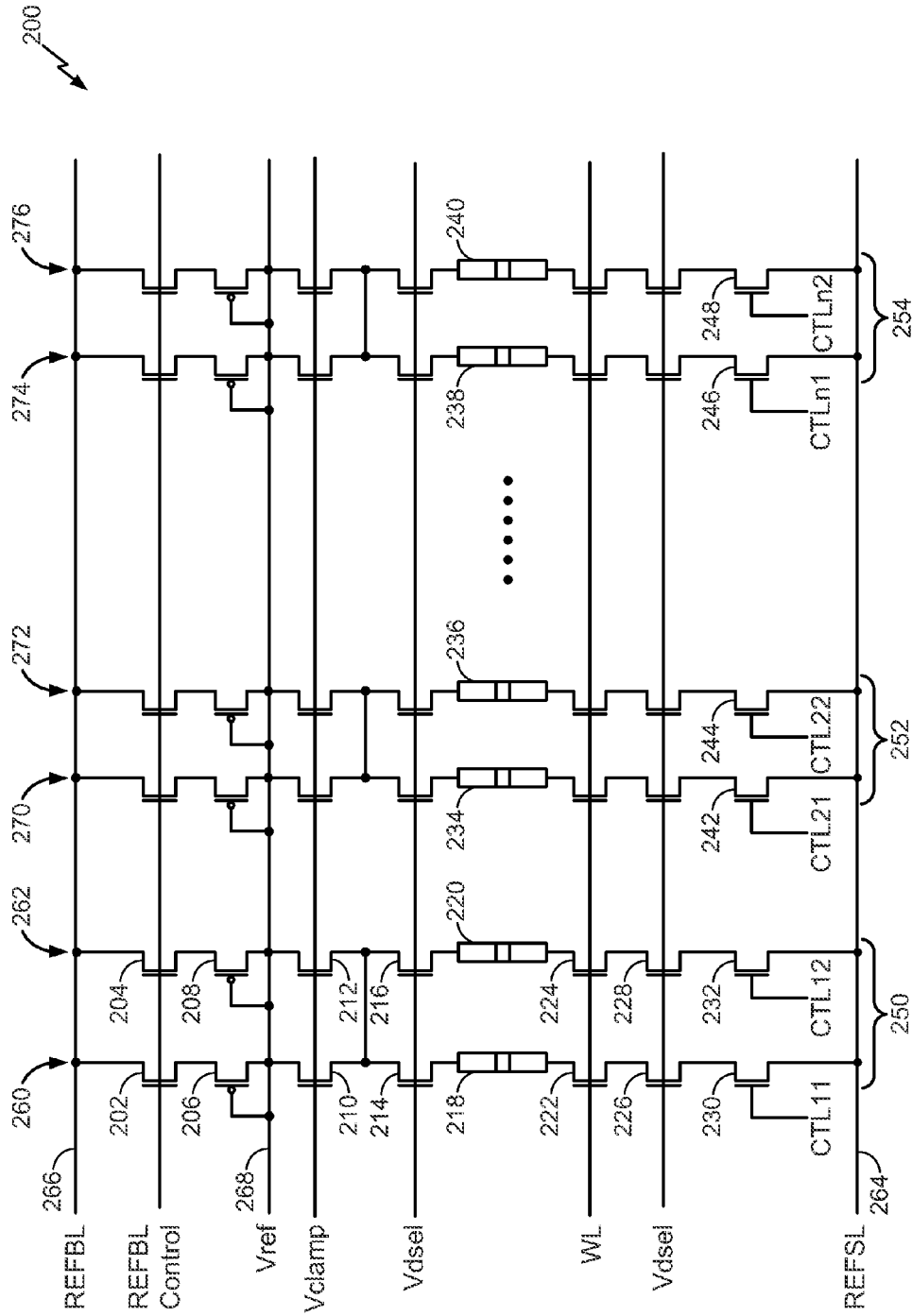
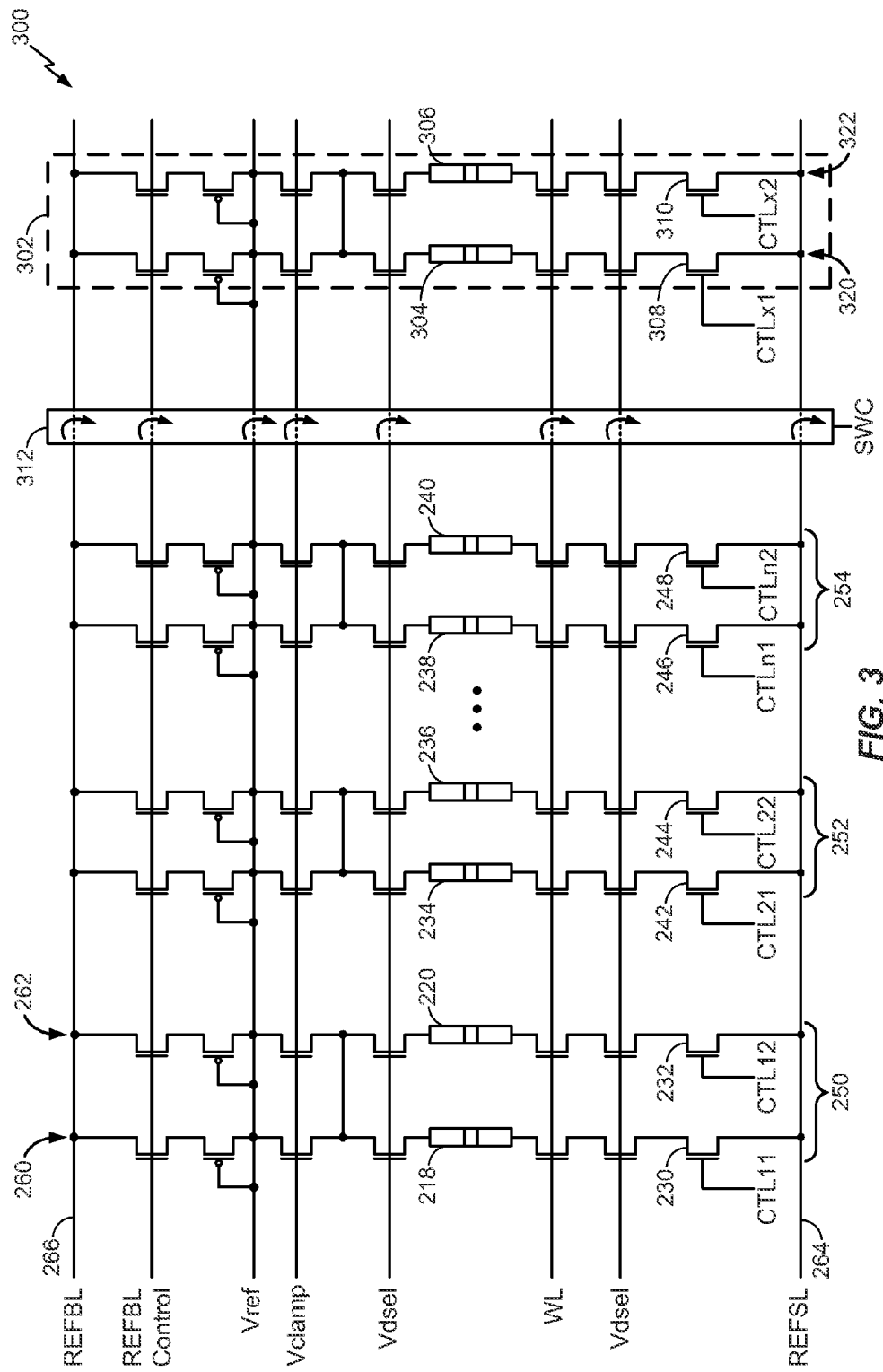
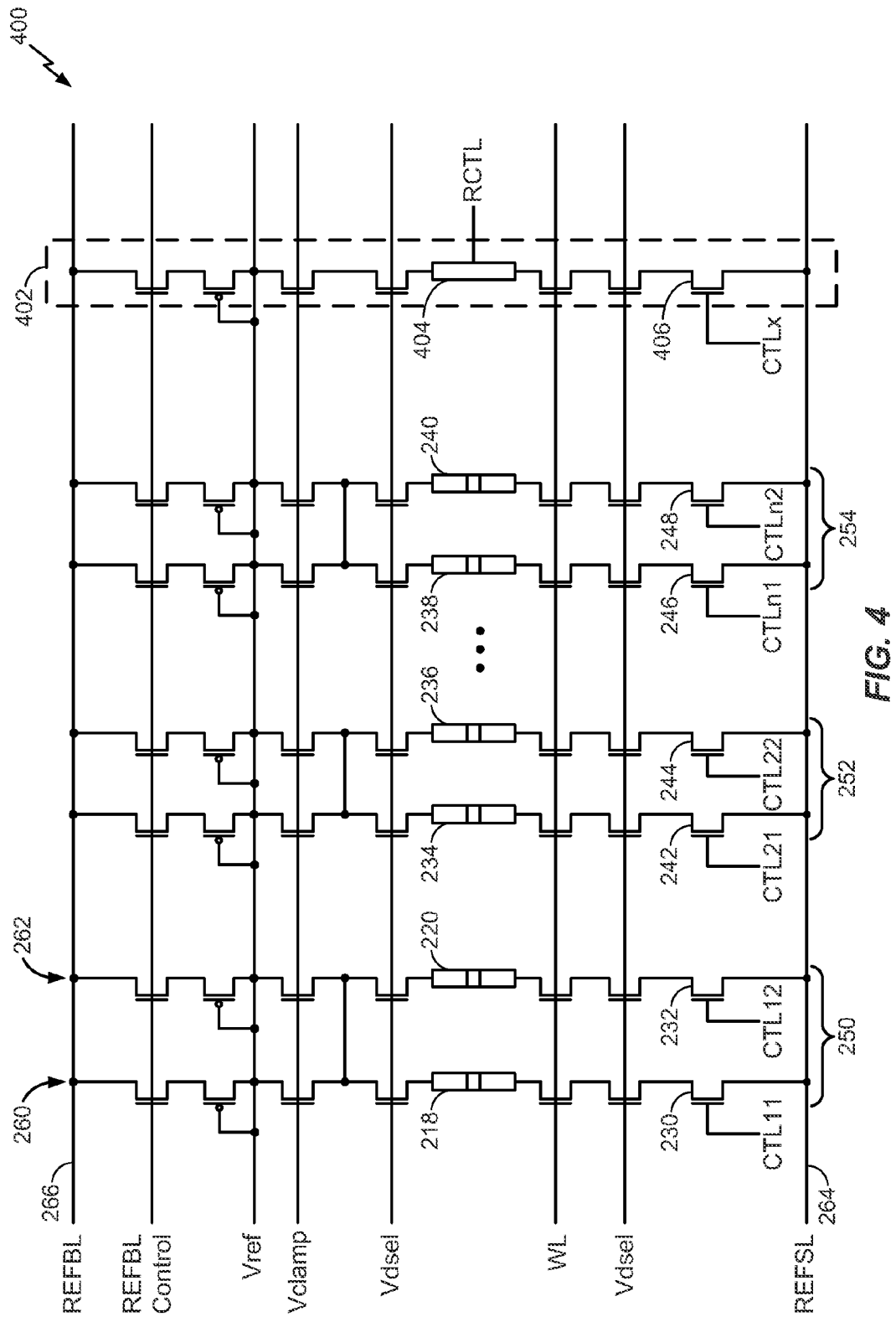


FIG. 1







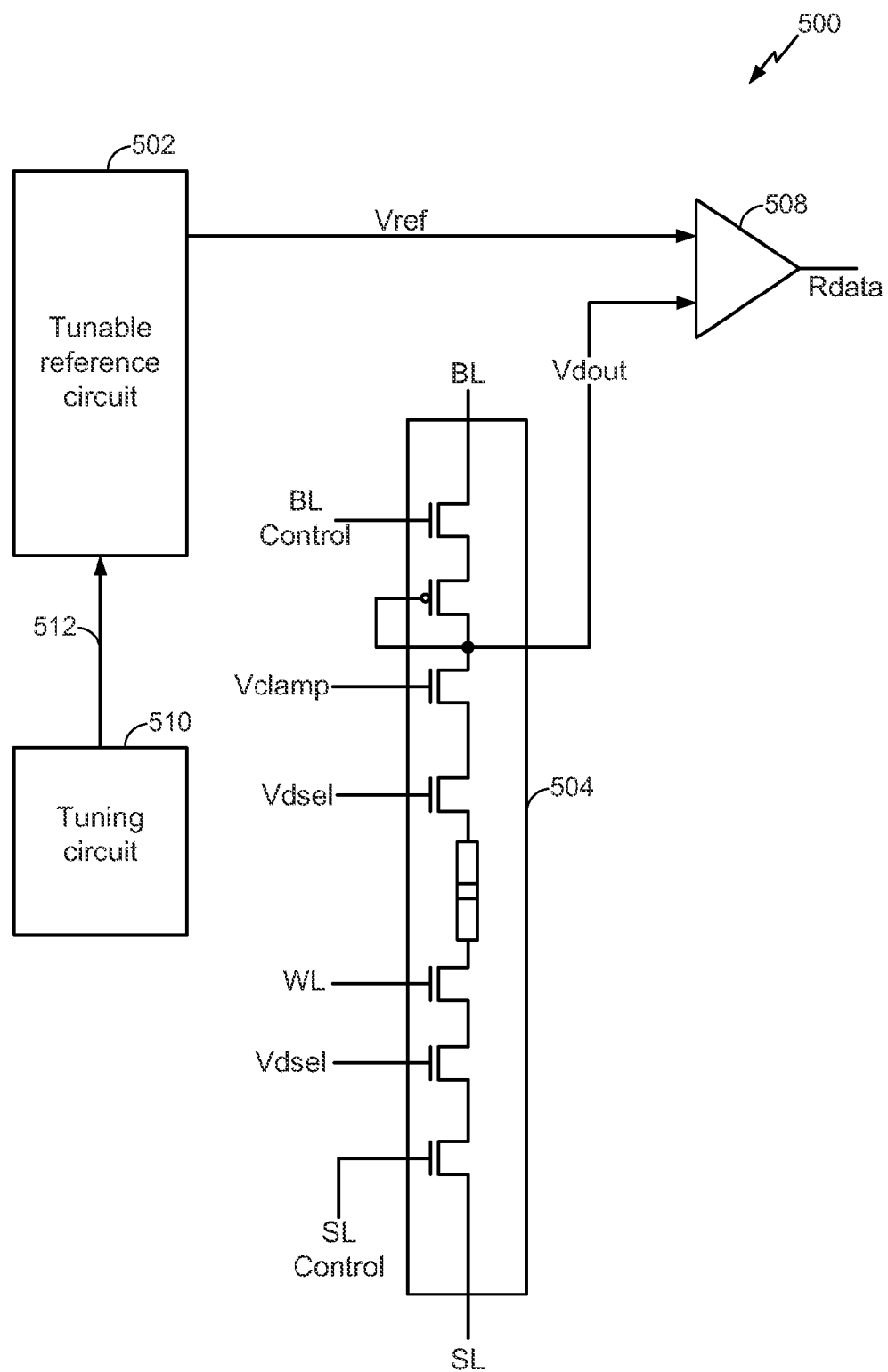
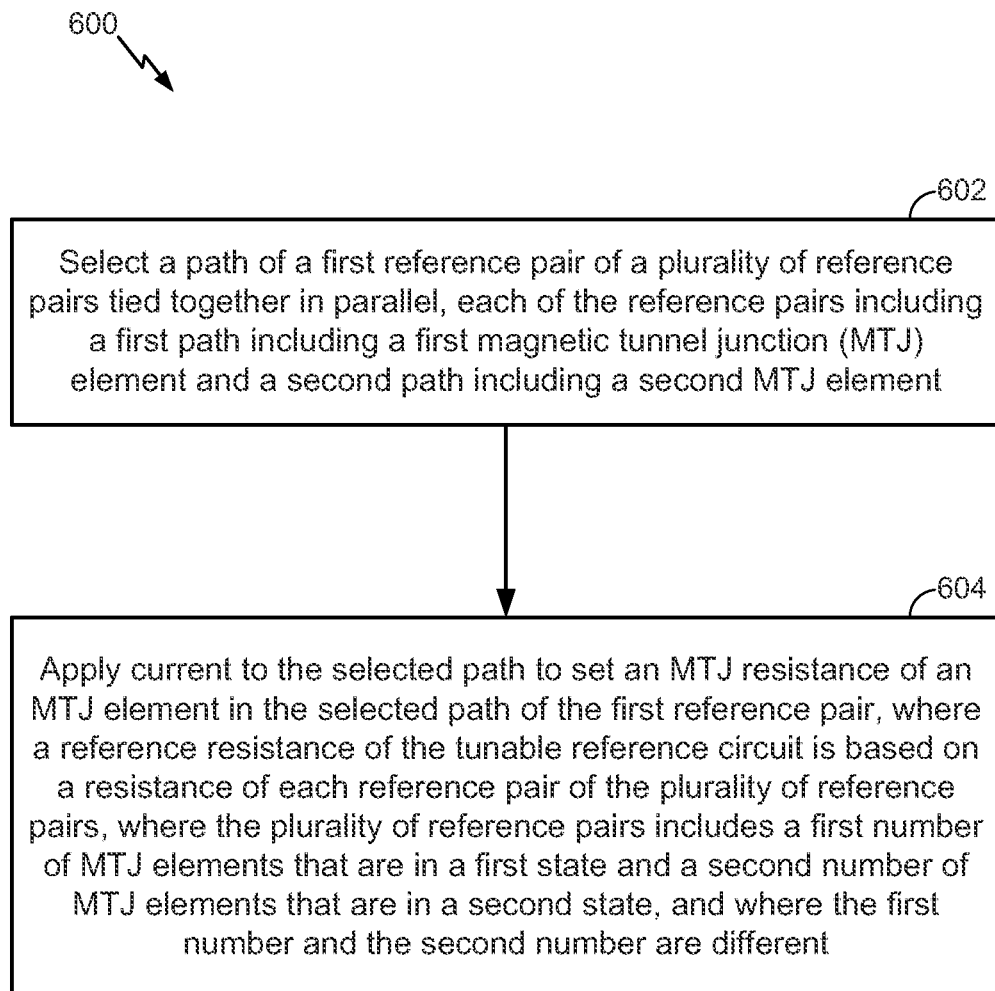


FIG. 5

**FIG. 6**

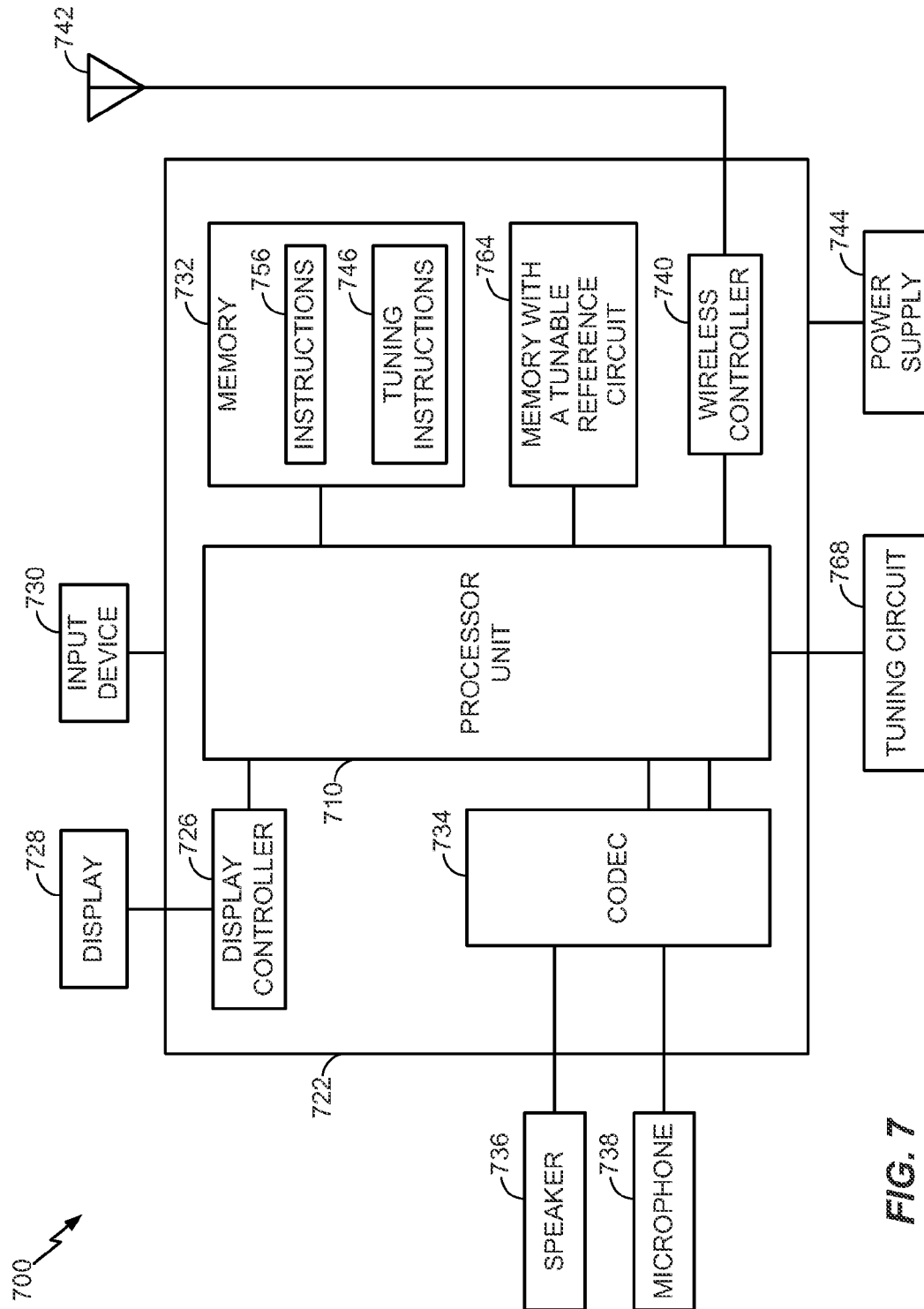
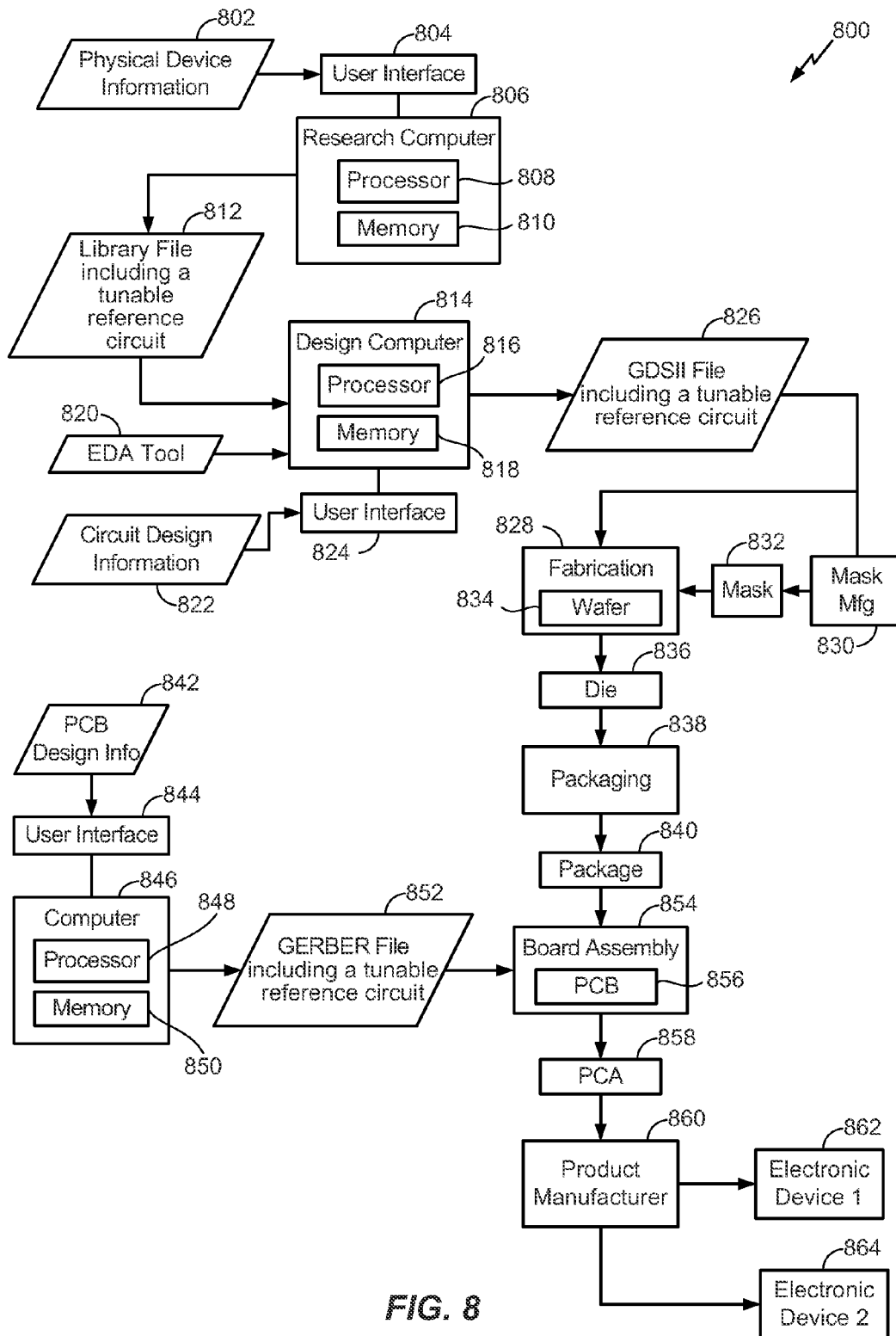


FIG. 7



TUNABLE REFERENCE CIRCUIT

I. FIELD

The present disclosure is generally related to adjusting a reference resistance of a reference circuit.

II. DESCRIPTION OF RELATED ART

Advances in technology have resulted in smaller and more powerful computing devices. For example, there currently exist a variety of portable personal computing devices, including wireless computing devices, such as portable wireless telephones, personal digital assistants (PDAs), and paging devices that are small, lightweight, and easily carried by users. More specifically, portable wireless telephones, such as cellular telephones and internet protocol (IP) telephones, can communicate voice and data packets over wireless networks. Further, many such wireless telephones include other types of devices that are incorporated therein. For example, a wireless telephone can also include a digital still camera, a digital video camera, a digital recorder, and an audio file player. Also, such wireless telephones can process executable instructions, including software applications, such as a web browser application, that can be used to access the Internet. These wireless telephones may also include memory devices that include magnetic tunnel junction (MTJ) memory elements.

An MTJ memory element may be used, for example, as a magnetic random access memory (MRAM) element of an MRAM device. An MTJ memory element may be in a parallel state or in an anti-parallel state. Each state of an MTJ memory element may correspond to a respective resistance of the MTJ memory element. A resistance of MTJ memory element that is low relative to a reference resistance may represent a first digital value. A resistance of the MTJ memory element that is high relative to the reference resistance may represent a second digital value. Whether a resistance of an MTJ memory element represents the first digital value or the second digital value may be determined by comparing an output voltage of the MTJ memory element to a reference voltage corresponding to the reference resistance. The output voltage of the MTJ element may correspond to the resistance of the MTJ memory element. Factors such as process variations and manufacturing defects may cause variations in the resistance of the MTJ memory element as well as in the reference resistance. Such resistance variations may result in inconsistent and inaccurate determination of a digital value represented by an output voltage of an MTJ memory element.

III. SUMMARY

A tunable reference circuit that provides a reference voltage is disclosed. The tunable reference circuit may provide a reference voltage to a sensing device (e.g., a sense amplifier) that uses the reference voltage to determine a digital value corresponding to an output voltage of a memory element, such as an MTJ element in an MRAM device. The reference voltage may correspond to a reference resistance of the tunable reference circuit, and the output voltage of the memory element may correspond to a resistance of the memory element.

The tunable reference circuit may include multiple reference pairs that are tied together in parallel and contribute to the reference resistance of the tunable reference circuit. Each reference pair may include a pair of paths that may also be tied together in parallel within each respective reference pair.

Each path in a reference pair may include an MTJ element that is selectively adjustable to be in a parallel state or in an anti-parallel state. The parallel state of the MTJ element may correspond to a low resistance (R_p) of the MTJ element, and the anti-parallel state of the MTJ element may correspond to a high resistance (R_{ap}) of the MTJ element. The reference resistance of the tunable reference circuit may be adjusted higher or lower by setting the number of MTJ elements that are in parallel state to be different from the number of MTJ elements that are in an anti-parallel state. Adjustment of the reference resistance correspondingly adjusts a reference voltage that is based on the reference resistance. Unequal numbers of MTJ elements in a parallel state and in an anti-parallel state may compensate for process variations and manufacturing defects that affect the reference resistance of the tunable reference circuit and a resistance of an MTJ memory element.

In a particular embodiment, a method of tuning a tunable reference circuit includes selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel. Each of the reference pairs includes a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element. The method also includes applying current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair. A reference resistance of the tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs. The plurality of reference pairs includes a first number of MTJ elements that are in a first state (e.g., parallel state) and a second number of MTJ elements that are in a second state (e.g., anti-parallel state), where the first number and the second number are different.

In another particular embodiment, a circuit includes a first reference pair that includes a first path and a second path. The first path includes a first magnetic tunnel junction (MTJ) element and the second path includes a second MTJ element. The circuit also includes a second reference pair that includes a third path and a fourth path. The third path includes a third MTJ element and the fourth path includes a fourth MTJ element. The first reference pair and the second reference pair are tied together in parallel. A reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements. The reference resistance of the circuit is adjustable by adjusting a resistance of one of the first and second MTJ elements.

In another particular embodiment, an apparatus includes means for selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel. Each of the reference pairs includes a first path that includes a first magnetic tunnel junction (MTJ) element and a second path that includes a second MTJ element. The apparatus also includes means for applying current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair. A reference resistance of the tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs. The plurality of reference pairs includes a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state, where the first number and the second number are different.

One particular advantage provided by at least one of the disclosed embodiments is adjustment of a reference resistance corresponding to a reference voltage that is used to determine a digital value associated with a resistance of an MTJ memory element. Adjustment of a reference resistance may improve reliability of a digital value that is determined based on a comparison of an output voltage of the MTJ memory element to the reference voltage. Further, adjustment

of a reference resistance may improve manufacturing yield of a memory device including memory MTJ elements by compensating for process variations and manufacturing defects that affect the reference resistance and the resistance of MTJ memory elements. To illustrate, reference pairs may be tied together in parallel to form a common reference circuit that may be used as a reference voltage source for multiple memory elements of a memory device. Because of parasitic routing resistance, a reference voltage level at a first location on a reference voltage line may be different from a reference voltage level at a second location on the reference voltage line. Additionally, due to processing variations, an MTJ memory element at a first location within a memory device may have a resistance that is different from a resistance of another MTJ memory element at a second location within the memory device. Thus, adjusting the reference voltage provided by the common reference circuit based on spatial locations of memory elements and of reference pairs may compensate for parasitic routing resistance and variations in resistances of MTJ memory elements.

Other aspects, advantages, and features of the present disclosure will become apparent after review of the entire application, including the following sections: Brief Description of the Drawings, Detailed Description, and the Claims.

IV. BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a particular illustrative embodiment of a tunable reference circuit;

FIG. 2 is a circuit diagram of a particular illustrative embodiment of the tunable reference circuit;

FIG. 3 is a circuit diagram of another particular illustrative embodiment of the tunable reference circuit;

FIG. 4 is a circuit diagram of another particular illustrative embodiment of the tunable reference circuit;

FIG. 5 is a block diagram of a particular illustrative embodiment of a system including the tunable reference circuit of FIGS. 1-4 to determine a digital value corresponding to an output of a memory element;

FIG. 6 is a flow chart of a particular illustrative embodiment of a method of adjusting a tunable reference circuit;

FIG. 7 is a diagram of wireless device including a memory with a tunable reference circuit; and

FIG. 8 is a data flow diagram of a particular illustrative embodiment of a manufacturing process to manufacture electronic devices that include a tunable reference circuit.

V. DETAILED DESCRIPTION

Referring to FIG. 1, a particular illustrative embodiment of a tunable reference circuit is depicted and generally designated 100. The tunable reference circuit 100 includes a first reference pair 102 and a second reference pair 104. The first reference pair 102 and the second reference pair 104 are tied together in parallel via a reference voltage line 124 and a line 122. The tunable reference circuit 100 may have a reference resistance at the reference voltage line 124 that is based on a resistance of the first reference pair 102 and a resistance of the second reference pair 104. For example, the reference resistance of the tunable reference circuit 100 may be an average of the resistances of the first reference pair 102 and the second reference pair 104. The tunable reference circuit 100 may have a reference voltage (V_{ref}) on the reference voltage line 124 that is based on the reference resistance of the tunable reference circuit 100. The reference voltage (V_{ref}) on the reference voltage line 124 may be adjusted by adjusting the reference resistance of the tunable reference circuit 100. In a

particular embodiment, the reference voltage (V_{ref}) on the reference voltage line 124 may be used to determine a digital value corresponding to an output voltage of a memory element, such as a magnetic random access memory (MRAM) element.

From spatial layout point of view, voltage levels of the reference voltage (V_{ref}) at various locations on the reference voltage line 121 may be different from each other due to parasitic routing resistance of the reference voltage line 124. For example, a voltage level of the reference voltage (V_{ref}) at a location that is close to the left side of the first reference pair 102 may be different from a voltage level of the reference voltage (V_{ref}) at another location that is close to the right side of the second reference pair 104. Thus, individually adjusting the resistance of the first reference pair 102 and the resistance of the second reference pair 104 may compensate for the effect of the parasitic routing resistance on the voltage level of the reference voltage (V_{ref}). Additionally, due to processing variations, MTJ memory elements of a memory device that are close to the first reference pair 102 may have resistances that are different from the resistances of MTJ memory elements of the memory device that are close to the second reference pair 104. The differences in the resistances of the memory elements may result in different desirable reference voltage levels for use with the different MTJ elements. Thus, adjusting the reference voltage based on a location of an MTJ memory element of a memory device may compensate for variations in resistances of the MTJ elements.

In a particular embodiment, the first reference pair 102 may include a first path 106 and a second path 108. The first path 106 may include a first MTJ element 110. The second path 108 may include a second MTJ element 112. The resistance of the first reference pair 102 may be based on a resistance of the first MTJ element 110 and a resistance of the second MTJ element 112. To illustrate, the first MTJ element 110 and the second MTJ element 112 may have a low resistance (R_p) or a high resistance (R_{ap}). In a particular embodiment, the low resistance (R_p) may correspond to a first state, and the high resistance (R_{ap}) may correspond to a second state. For example, the first state may correspond to a parallel state of an MTJ element, and the second state may correspond to an anti-parallel state of the MTJ element.

In a particular embodiment, the first MTJ element 110 may be in the parallel state or in the anti-parallel state based on a direction of a write current that passes through the first path 106. Similarly, the second MTJ element 112 may be set in the parallel state or in the anti-parallel state based on a direction of a write current that passes through the second path 108. In a particular embodiment, the resistance of the first reference pair 102 may be an equivalent resistance of the resistance of the first MTJ element 110 and the resistance of the second MTJ element 112 that is in parallel with the first MTJ element 110.

In a particular embodiment, the second reference pair 104 includes a third path 114 and a fourth path 116. The third path 114 includes a third MTJ element 118 and the fourth path 116 includes a fourth MTJ element 120. The resistance of the second reference pair 104 may be based on a resistance of the third MTJ element 118 and a resistance of the fourth MTJ element 120. To illustrate, the third MTJ element 118 and the fourth MTJ element 120 may have the low resistance (R_p) or the high resistance (R_{ap}). The low resistance (R_p) may correspond to the first state, and the high resistance (R_{ap}) may correspond to the second state. For example, the first state may correspond to a parallel state of an MTJ element, and the second state may correspond to an anti-parallel state of the MTJ element.

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In a particular embodiment, the third MTJ element 118 may be in the parallel state or in the anti-parallel state based on a direction of a write current that passes through the third path 114. Similarly, the fourth MTJ element 120 may be set in the parallel state or in the anti-parallel state based on a direction of a write current that passes through the fourth path 116. In a particular embodiment, the resistance of the second reference pair 104 may be an equivalent resistance of the resistance of the third MTJ element 118 and the resistance of the fourth MTJ element 120 that is in parallel with the third MTJ element 118.

In a particular embodiment, the reference resistance of the tunable reference circuit 100 may be based on a resistance of each of the first MTJ element 110, the second MTJ element 112, the third MTJ element 118, and the fourth MTJ element 120. For example, the reference resistance of the tunable reference circuit 100 may be adjustable by adjusting a resistance of one or more of the first MTJ element 110 and the second MTJ element 112. The reference resistance of the tunable reference circuit 100 may also be adjustable by adjusting a resistance of one or more of the third MTJ element 118 and the fourth MTJ element 120.

In a particular embodiment, a number of the MTJ elements 110, 112, 118, 120 that are in a first state (e.g., the parallel state) may be different from a number of the MTJ elements 110, 112, 118, 120 that are in a second state (e.g., the anti-parallel state). To illustrate, the first MTJ element 110 and the second MTJ element 112 may be adjusted to be in the same state as each other and the third MTJ element 118 may be adjusted to be in a different state from the fourth MTJ element 120. In a particular embodiment, the first MTJ element 110, the second MTJ element 112, and the third MTJ element 118 may be adjusted to be in the parallel state, and the fourth MTJ element 120 may be adjusted to be in the anti-parallel state. Alternatively, in another embodiment, a number of the MTJ elements 110, 112, 118, 120 that are in a first state (e.g., the parallel state) may be equal to a number of the MTJ elements 110, 112, 118, 120 that are in a second state (e.g., the anti-parallel state).

During operation, the reference voltage (V_{ref}) on the reference voltage line 124 may be adjusted higher or lower by adjusting the reference resistance of the tunable reference circuit 100 higher or lower, respectively. The reference resistance of the tunable reference circuit 100 may be adjusted by adjusting the state of one or more of the first MTJ element 110, the second MTJ element 112, the third MTJ element 118, and the fourth MTJ element 120. For example, the resistance of one or more of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 may be adjusted such that a number of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 in the first state is different from a number of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 in the second state. To illustrate, a respective write current may be supplied to each of the first path 106, the second path 108, the third path 114, and the fourth path 116. Each of the first MTJ element 110, the second MTJ element 112, the third MTJ element 118, and the fourth MTJ element 120 may be set to be in the parallel state or in the anti-parallel state based on a direction of the respective write current. For example, the first MTJ element 110, the second MTJ element 112, and the third MTJ element 118 may be configured to be in a parallel state corresponding to the low resistance (R_p) and the fourth MTJ element 120 may be configured to be in the anti-parallel state corresponding to the high resistance (R_{ap}).

Following the adjustment of the reference resistance of the tunable reference circuit 100, the reference voltage (V_{ref}) corresponding to the reference resistance of the tunable ref-

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erence circuit 100 may be used to determine a digital value corresponding to an output voltage of an MTJ memory element that is based on a resistance of the MTJ memory element. A respective read current may be applied to a source line or a bit line of a memory element and to each of the first path 106, the second path 108, the third path 114, and the fourth path 116. The output voltage of the MTJ memory element may be compared to the reference voltage (V_{ref}) corresponding to the reference resistance of the tunable reference circuit 100 to determine the digital value corresponding to the output voltage of the MTJ memory element.

By adjusting a resistance of one or more of the first MTJ element 110, the second MTJ element 112, the third MTJ element 118, and the fourth MTJ element 120, the reference resistance of the tunable reference circuit 100 may be adjusted higher or lower. The reference voltage (V_{ref}) may be correspondingly adjusted higher or lower as a result of adjusting the reference resistance of the tunable reference circuit 100. Adjustment of the reference voltage (V_{ref}) may improve the sensing margin of a sense amplifier and reliability of a digital value that is determined as corresponding to an output voltage of an MTJ memory element based on the output voltage of the MTJ memory element and the reference voltage (V_{ref}). In addition, manufacturing yield of memory devices that include the MTJ memory element may be improved as a result of compensating for process variations and manufacturing defects by adjusting the reference resistance of the tunable reference circuit 100. Additionally, because of parasitic routing resistance, the reference voltage (V_{ref}) may have different voltage levels at various locations on the reference voltage line 124. To overcome effects of parasitic routing resistance, a voltage level of the reference voltage (V_{ref}) at a particular location on the reference voltage line 124 may be preferably adjusted by changing the resistance of a reference pair that is close to the particular location. Further, due to processing variations, MTJ memory elements at different locations within a memory device may have different resistances. Accordingly, voltage levels of the reference voltage (V_{ref}) at different locations on the reference voltage line 124 may be adjusted to compensate for variations in resistances of MTJ memory elements that are close to particular locations on the reference voltage line 124. Thus, the sensing margin of a sense amplifier may be improved by adjusting the reference voltage based on spatial location of an MTJ memory element of a memory device.

To illustrate, adjusting the resistance of one or more of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 such that the number of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 in the first state is different from the number of the first, second, third, and fourth MTJ elements 110, 112, 118, 120 in the second state has a number of technical advantages.

For example, an initial configuration of the tunable reference circuit 100 may include reference pairs 102, 104, where each reference pair includes an MTJ element that is in a parallel state and an MTJ element that is in anti-parallel state. The reference resistance of the tunable reference circuit 100 may be an average of the resistance of each reference pair 102, 104, and the resistance of each particular pair may be an equivalent resistance of a resistance of each of the two MTJ elements that are tied together in parallel in the particular pair. Such a configuration may provide a reference resistance of the tunable reference circuit that is desirably close to half way between a high resistance of an MTJ memory element and a low resistance of the MTJ memory element. However, due to factors such as process variations and manufacturing defects, the reference resistance of the tunable reference circuit may

be, for example, closer to either a high resistance of the MTJ memory element or to a low resistance of the MTJ memory. Such deviations from a desirable relationship between the reference resistance of the tunable reference circuit **100** and a resistance of the MTJ memory element may impact reliable determination (sensing) of a digital value that corresponds to the resistance of the MTJ memory element. Unreliability of determined digital values may adversely impact manufacturing yield of a memory device that includes the MTJ memory element.

By selecting a path in a reference pair of a tunable reference circuit and adjusting the resistance of an MTJ element in the selected path to a low resistance (e.g., a low resistance corresponding to a first state such as a parallel state) or a high resistance (e.g. a high resistance corresponding to a second state such as an anti-parallel state), a resistance of the reference pair may be adjusted lower or higher. The adjustment of the resistance of the MTJ element in the selected path may correspondingly adjust the reference resistance of the tunable reference circuit such that the reference resistance is balanced between a high resistance and a low resistance of the MTJ element. An adjustment of a resistance of an MTJ element in the selected path of a reference pair may result in the reference pair having both MTJ elements in a parallel state or in an anti-parallel state and in the tunable reference circuit having unequal numbers of MTJ elements in the parallel state and MTJ elements in the anti-parallel state. Thus, a tunable reference circuit that has unequal numbers of MTJ elements in a parallel state and MTJ elements in an anti-parallel state may have a reference resistance that is desirably balanced between a high resistance of the MTJ memory element and a low resistance of the MTJ memory element such that reliability of digital values that are determined (sensed) based on the resistance of the MTJ memory element is improved. Improvements in the reliability of digital values determined (sensed) based on the resistance of the MTJ memory element may result in improved manufacturing yield.

Although FIG. 1 illustrates two reference pairs, **102**, **104** in the tunable reference circuit **100**, the tunable reference circuit **100** may have greater than or less than two reference pairs. In addition, each of the first path **106**, the second path **108**, the third path **114**, and the fourth path **116** may have one or more MTJ elements in series with the first MTJ element **110**, the second MTJ element **112**, the third MTJ element **118**, and the fourth MTJ element **120**, respectively.

Referring to FIG. 2, a particular illustrative embodiment of a tunable reference circuit is depicted and generally designated **200**. The tunable reference circuit **200** may provide a reference voltage (V_{ref}) that is based on a reference resistance of the tunable reference circuit **200** for use in determining a digital value corresponding to an output voltage of a memory element. The tunable reference circuit **200** may include a first reference pair **250**, a second reference pair **252**, and an nth reference pair **254**. The first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may be tied together in parallel. The first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may be tied together via a reference voltage line at the reference voltage (V_{ref}) **268**, a reference bit line signal (REFBL) at the reference bit line **266**, and a reference source line **264** that is configured to carry a reference source line signal (REFSL). In a particular embodiment, the first reference pair **250** and the second reference pair **252** may correspond to the first reference pair **102** and to the second reference pair **104** of FIG. 1, respectively.

In a particular embodiment, the reference resistance of the tunable reference circuit **200** at the reference voltage line **268**

may be based on a resistance of each of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. For example, the reference resistance of the tunable reference circuit **200** may be an average of the resistance of each of first reference pair **250**, the second reference pair **252**, and an nth reference pair **254**. The reference resistance of the tunable reference circuit **200** may be adjusted by adjusting a resistance of one or more of the first reference pair **250**, the second reference pair **252**, and an nth reference pair **254**. In a particular embodiment, the reference voltage (V_{ref}) on the reference voltage line **268** may be changed by adjusting the reference resistance of the tunable reference circuit **200**.

In a particular embodiment, the reference resistance of the tunable reference circuit **200** may be adjusted by adjusting a resistance of the first reference pair **250**. The first reference pair **250** may include a first path **260** and a second path **262**. The first path **260** may include a first MTJ element **218** and a first transistor **230**. The first MTJ element **218** may be coupled to a word line transistor **222** and to a first data select transistor **214**. A voltage clamp transistor **210** may be coupled to the first data select transistor **214** and to a load transistor **206**. In a particular embodiment, the load transistor **206** may be op-channel metal-oxide-semiconductor (PMOS) transistor. A drain terminal and a gate terminal of the load transistor **206** may be coupled to the reference voltage line **268**. The load transistor **206** may be coupled to a source terminal of a reference bit line control transistor **202**. The drain terminal of the bit line control transistor **202** may be coupled to the reference bit line **266**. The word line transistor **222** may be coupled to a second data select transistor **226** that is coupled to a drain terminal of the first transistor **230**. The source terminal of the first transistor **230** may be coupled to the reference source line **264**.

In a particular embodiment, at least one control signal may be asserted to enable adequate current to flow through the first MTJ element **218**. For example, a word line signal (WL), a data select signal (V_{dsel}), a voltage clamp signal (V_{clamp}), a reference bit line control signal (REFBL control), and the first reference source line control signal (CTL11) may be asserted to enable adequate current to flow through the first MTJ element **218**.

In a particular embodiment, the first path **260** may be selected by asserting a first reference source line control signal (CTL11) that is provided to a gate terminal of the first transistor **230**. The first path **260** may be configured to receive a current to set an MTJ resistance of the first MTJ element **218**. For example, after selecting the first path **260** by asserting the first reference source line control signal (CTL11), a write current may be applied to the selected first path **260** to set the MTJ resistance of the first MTJ element **218**. In an alternative embodiment, the first path **260** may be selected by asserting the first reference source line control signal (CTL11) after or substantially simultaneously with applying the write current to the first path **260**.

In a particular embodiment, the first path **260** may be configured to receive the write current via the reference bit line **266** or via the reference source line **264**. For example, the first path **260** may be configured to receive the write current via the reference bit line **266** to set the first MTJ element **218** in a first state. The first path **260** may also be configured to receive the write current via the reference source line **264** to set the first MTJ element **218** in a second state.

In a particular embodiment, a first resistance of the first MTJ element **218** may correspond to the first state, and a second resistance of the first MTJ element **218** may correspond to the second state. To illustrate, the first state may correspond to a parallel state of the first MTJ element **218**, and

the second state may correspond to an anti-parallel state of the first MTJ element **218**. In a particular embodiment, the second resistance may be greater than the first resistance. For example, the first resistance may correspond to a low resistance (R_p), and the second resistance may correspond to a high resistance (R_{ap}).

In a particular embodiment, the second path **262** may include a second MTJ element **220** and a first transistor **232**. The second MTJ element **220** may be coupled to a word line transistor **224** and to a first data select transistor **216**. A source terminal of a voltage clamp transistor **212** may be coupled to a source terminal of the voltage clamp transistor **210** of the first path **260**. The voltage clamp transistor **212** may also be coupled to the first data select transistor **216** and to a load transistor **208**. In a particular embodiment, the load transistor **208** may be a PMOS transistor. A drain terminal and a gate terminal of the load transistor **208** may be coupled to the reference voltage line **268**. The load transistor **208** may be coupled to a source terminal of a reference bit line control transistor **204**. The drain terminal of the reference bit line control transistor **204** may be coupled to the reference bit line **266**. The word line transistor **224** may be coupled to a second data select transistor **228** that is coupled to a drain terminal of a second transistor **232**. The source terminal of the second transistor **232** may be coupled to the reference source line **264**.

In a particular embodiment, the second path **262** may be configured to receive a write current to set the MTJ resistance of the second MTJ element **220**. For example, the second path **262** may be configured to receive the write current via the reference bit line **266** to set the second MTJ element **220** in a first state and to receive the write current via the reference source line **264** to set the second MTJ element **220** in a second state. In a particular embodiment, the second path **262** may be selected by asserting a second reference source line control signal (CTL12) that is provided to gate terminal of the second transistor **232**.

In a particular embodiment, the first state may correspond to a parallel state of the second MTJ element **220** corresponding to a first resistance of the second MTJ element **220**, and the second state may correspond to an anti-parallel state of the second MTJ element **220** corresponding to a second resistance of the second MTJ element **220**. To illustrate, the first resistance may be greater than the second resistance. For example, the first resistance may correspond to a low resistance (R_p), and the second resistance may correspond to a high resistance (R_{ap}).

In a particular embodiment, the control signal may be asserted to enable current to flow through the second MTJ element **220**. For example, the word line signal (WL), the data select signal (V_{dsel}), the voltage clamp signal (V_{clamp}), the reference bit line control signal (REFBL control), and the second reference source line control signal (CTL12) may be asserted to enable adequate current to flow through the second MTJ element **220**.

In a particular embodiment, after selecting the second path **262** by asserting the second reference source line control signal (CTL12), a write current may be applied to the selected second path **262** to set the resistance of the second MTJ element **220**. In an alternative embodiment, the second path **262** may be selected by asserting the second signal (CTL12) after or substantially simultaneously with applying the write current to the second path **262**.

In a particular embodiment, the reference resistance of the tunable reference circuit **200** may be adjusted by adjusting a resistance of the second reference pair **252**. The second reference pair **252** may have a similar structure as the first

reference pair **250**. For example, the second reference pair **252** may have a first path **270** and a second path **272**. The second reference pair **252** may have a first MTJ element **234** in the first path **270** and a second MTJ element **236** in the second path **272**. A third reference source line control signal (CTL21) may be provided to a gate terminal of a first transistor **242** in the first path **270** of the second reference pair **252**. A fourth reference source line control signal (CTL22) may be provided, to a gate terminal of a second transistor **244** of the second path **272** of the second reference pair **252**. The first path **270** of the second reference pair **252** may be selected by asserting the reference source line control signal (CTL21). Similarly, the second path **272** of the second reference pair **252** may be selected by asserting the reference source line control signal (CTL22). The first path **270** may be configured to receive a current to set an MTJ resistance of the first MTJ element **234** in a similar manner as described with respect to the first path **260** in the first reference pair **250**. The second path **272** may be configured to receive a current to set an MTJ resistance of the second MTJ element **236** in a similar manner as described with respect to the second path **262** in the first reference pair **250**.

In a particular embodiment, the reference resistance of the tunable reference circuit **200** may be adjusted by adjusting a resistance of the nth reference pair **254**. The nth reference pair **254** has a similar structure as the first reference pair **250** and, the second reference pair **252**. For example, a first path **274** of the nth reference pair **254** may include a first NTH element **238** and a first transistor **246**. A second path **276** of the nth reference pair **254** may include a second, nth element **240** and a second transistor **248**. The first path **274** of the nth reference pair **254** may be selected by asserting a fifth reference source line control signal (CTLn1) that is provided to a gate terminal of the first transistor **246**. Similarly, the second path **276** of the nth reference pair **254** may be selected by asserting a reference source line control signal (CTLn2) that is provided to a gate terminal of the second transistor **248**. The first path **274** may be configured to receive a current to set an MTJ resistance of the first MTJ element **238** in a similar manner as described with respect to the first path **260** in the first reference pair **250**. The second path **276** may be configured to receive a current to set an MTJ resistance of the second MTJ element **240** in a similar manner as described with respect to the second path **262** in the first reference pair **250**.

During operation, the reference resistance of the tunable reference circuit **200** may be adjusted by adjusting the resistance of one or more of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. In a particular embodiment, the reference resistance of the tunable reference circuit **200** is adjusted after a test (e.g., a self-test) is performed on the tunable reference circuit **200** to determine initial resistance of the tunable reference circuit **200**. For example, the resistance of one or more of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may be adjusted such that a number of MTJ elements having a low resistance (R_p) is different from a number of MTJ elements having a high resistance (R_{ap}). Due to parasitic routing resistance, each reference pair **250**, **252**, **254** may affect the reference voltage (V_{ref}) differently at a particular location on the reference voltage line **268**. Additionally, the resistances of the reference pairs **250**, **252**, and **254** may be different from each other due to processing variations. Thus, an algorithm for tuning a specific reference pair based on spatial location of each reference pair **250**, **252**, **254** and variations in resistances of the reference pairs **250**, **252**, and **254** may improve a sensing margin of a sense amplifier.

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To illustrate, the resistance of the first reference pair **250** may be adjusted to adjust the reference resistance of the tunable reference circuit **200**. To adjust the resistance of the first reference pair **250**, the first reference source line control signal (CNTL**11**) may be asserted to select the first path **260**. The word line signal (WL), the data select signal (Vdsel), the voltage clamp signal (Vclamp), and the reference bit line control signal (REFBL control) may be asserted to turn on the word line transistor **222**, the data select transistors **214**, **226**, the voltage clamp transistor **210**, and the bit line control transistor **202**, respectively. Turning on the word line transistor **222**, the data select transistors **214**, **226**, the voltage clamp transistor **210**, and the bit line control transistor **202** enables a write current to flow through the first MTJ element **218** to set the resistance of the first MTJ element **218**. The write current may be applied to the reference bit line **266** to set the resistance of the first MTJ element **218** to a low resistance (Rp) or to a high resistance (Rap). Alternatively, the write current may be applied to the reference source line **264** to set the resistance of the first element **218** to a low resistance (Rp) or to a high resistance (Rap).

Following the adjustment of the reference resistance of the tunable reference circuit **200**, the reference voltage (Vref) corresponding to the reference resistance of the tunable reference circuit **200** may be used to determine (sense) a digital value corresponding to an output voltage of an MTJ memory element. A respective read current may be applied to the reference source line **264** and to a source line of a memory element. Alternatively, a respective read current may be applied to the reference bit line **266** and to a bit line of the memory element. The output voltage of the MTJ memory element may be compared to the reference voltage (Vref) to determine (sense) the digital value corresponding to the output voltage of the MTJ memory element.

By adjusting the resistance of one or more of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**, the reference resistance of the tunable reference circuit **200** may be adjusted higher or lower. The reference voltage (Vref) may be correspondingly adjusted higher or lower as a result of adjusting the reference resistance of the tunable reference circuit **200**. Adjustment of the reference voltage (Vref) may improve the reliability of a digital value corresponding to an output voltage of an MTJ memory element that is determined (sensed) based on the output voltage of the MTJ memory element and the reference voltage (Vref). By adjusting a resistance of a specific reference pair, overall reference resistance of the tunable reference circuit **200** and the reference resistance at a particular location on the reference voltage line may be tuned to increase sensing margin for all MTJ elements in a memory device as well as for particular MTJ memory elements in the memory device. In addition, manufacturing yield of memory devices that include the MTJ memory element may be improved as a result of compensating for process variations and manufacturing defects by adjusting the reference resistance of the tunable reference circuit **200**.

Although FIG. 2 illustrates three reference pairs **250**, **252**, **254**, the tunable reference circuit **200** may include greater than or less than three reference pairs, in addition, although the operation of adjusting the reference resistance of the tunable reference circuit **200** is described with respect to the first reference pair **250**, the resistance of each of the second reference pair **252** and the nth reference pair **254** may be adjusted in a similar manner as described with respect to the first reference pair **250** to adjust the reference resistance of the tunable reference circuit **200**. Further, the resistance of the first reference pair **250** may also be adjusted by adjusting the

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resistance of the second MTJ element **220** in a similar manner as described with respect to the first MTJ element **218**. Adjusting a specific reference pair based on an optimizing algorithm may improve overall sensing margin for all NTH elements in a memory device and also improve sensing margin for particular MTJ memory elements in the memory device. Such improvements in sensing margin may improve manufacturing yield of MRAM devices.

Referring to FIG. 3, a particular illustrative embodiment of a tunable reference circuit is depicted and generally designated **300**. The tunable reference circuit **300** may provide a reference voltage (Vref) that is based on a reference resistance of the tunable reference circuit **300** for use in determining (sensing) a digital value corresponding to an output voltage of a memory element. The tunable reference circuit **300** may include the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, a spare reference pair **302**, and bank of switches **312**. The first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may be coupled together in parallel. The spare reference pair **302** may be tied in parallel to the first reference pair **250**, to the second reference pair **252**, and to the nth reference pair **254** via the bank of switches **312**. In a particular embodiment, the reference resistance of the tunable reference circuit **300** may be adjusted by adjusting the reference resistance of one or more of the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and the spare reference pair **302**.

In a particular embodiment, the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may correspond to the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** of FIG. 2.

In a particular embodiment, the bank of switches **312** may be configured to receive a switch control signal (SWC) to control the operation of switches in the bank of switches **312**. For example, the switch control signal (SWC) may be asserted to close the switches in the bank of switches **312** to couple the spare reference pair **302** to the first reference pair **250**, to the second reference pair **252**, and to the nth reference pair **254**. The switch control signal (SWC) may also be deasserted to open the switches in the bank of switches **312** to decouple the spare reference pair **302** from the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. In a particular embodiment, one or more of the switches in the switch bank **312** may be n-channel metal-oxide-semiconductor (NMOS) transistors, p-channel metal-oxide-semiconductor (PMOS) transistors, or complimentary metal-oxide-semiconductor (CMOS) transistors. For example, the switch control signal (SWC) may be provided to a gate terminal of each transistor in the bank of switches **312**.

In a particular embodiment, the reference resistance of the tunable reference circuit **300** may be adjusted by adjusting the reference resistance of the spare reference pair **302**. The spare reference pair **302** may have a similar structure as the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. For example, the spare reference pair **302** may include a first path **320** and a second path **322**. The first path **320** may be configured receive the write current via the reference bit line **266** or via the reference source line **264**. The spare reference pair **302** may include a first spare MTJ element **304** in the first path **320** and a second spare MTJ element **306** in the second path **322**. The reference resistance of the tunable reference circuit **300** may be adjustable by adjusting a resistance of one or more of the first spare MTJ element **304** and the second spare MTJ element **306**. For example, the reference resistance of the tunable reference circuit **300** may be adjustable by adjusting a resistance of the first spare MTJ

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element **304**. To illustrate, the first spare reference source line control signal (CTLx1) may be provided to a gate terminal of a first spare transistor **308** in the first path **320**. A second spare reference source line control signal (CTLx2) may be provided to a gate terminal of a second spare transistor **310** in the second path **322**. The first path **320** may be selected by asserting the first spare reference source line control signal (CTLx1). Similarly, the second path **322** may be selected by asserting the second spare reference source line control signal (CTLx2). In a particular embodiment, the first path **320** may be configured to receive a current to set an MTJ resistance of the first spare MTJ element **304** in a similar manner as described with respect to the first path **260** in the first reference pair **250** of FIG. 2. The second path **322** may be configured to receive a current to set an MTJ resistance of the second spare MTJ element **306** in a similar manner as described with respect to the second path **262** in the first reference pair **250** of FIG. 2.

In a particular embodiment, the resistance of one or more of the first spare MTJ element **304** and the second spare MTJ element **306** may be adjusted such that a number of MTJ elements in the tunable reference circuit **300** having a low resistance (R_p) (e.g., in a parallel state) is different from a number of MTJ elements in the tunable reference circuit **300** having a high resistance (R_{ap}) (e.g., in an anti-parallel state). In another particular embodiment, the resistance of one or more of the first spare MTJ element **304** and the second spare MTJ element **306** may be adjusted such that a number of MTJ elements in the tunable reference circuit **300** having a low resistance (R_p) (e.g., in a parallel state) is equal to a number of MTJ elements in the tunable reference circuit **300** having a high resistance (R_{ap}) (e.g., in an anti-parallel state).

In a particular embodiment, the spare reference pair **302** may be included in an array of reference pairs that includes the first reference pair **250** and the second reference pair **252**. In an alternative embodiment, the spare reference pair **302** may be external to the array of reference pairs that includes the first reference pair **250** and the second reference pair **252**. In another particular embodiment, the spare reference pair **302** may include only the first path **320**.

During operation, the reference resistance of the tunable reference circuit **300** may be adjusted by adjusting the resistance of one or more of the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and the spare reference pair **302**. For example, the resistance of one or more of the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and the spare reference pair **302** may be adjusted such that a number of MTJ elements having a low resistance (R_p) is different from a number of MTJ elements having a high resistance (R_{ap}). To illustrate, the switch control signal (SWC) may be asserted to couple the spare reference pair **302** to the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. To adjust the resistance of the spare reference pair **302**, the spare reference source line control signal (CNTLx1) may be asserted to select the first path **320**. The word line signal (WL), the data select signal (Vdsel), the voltage clamp signal (Vclamp), and the reference bit line control signal (REFBL control) may be asserted to turn on transistors in the spare reference pair **302**. A write current may be applied to the first path **320** to set the resistance of the first spare MTJ element **304** to a low resistance (R_p) or to a high resistance (R_{ap}). The resistance of the second spare MTJ element **306** may be adjusted in a similar manner as described with respect to the first spare MTJ element **304**.

Following the adjustment of the reference resistance of the tunable reference circuit **300**, the reference voltage (V_{ref})

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corresponding to the reference resistance of the tunable reference circuit **300** may be used to determine (sense) a digital value corresponding to an output voltage of an MTJ memory element, as described with respect to FIG. 2.

By coupling the spare reference pair **302** to the first reference pair **250**, to the second reference pair **252**, and to the nth reference pair **254** and adjusting the resistance of the spare reference pair **302**, the reference resistance of the tunable reference circuit **300** may be adjusted. The reference voltage (V_{ref}) may be correspondingly adjusted higher or lower as a result of adjusting the reference resistance of the tunable reference circuit **300**. Adjustment of the reference voltage (V_{ref}) may improve the reliability of a digital value corresponding to an output voltage of an MTJ memory element that is determined (sensed) based on the output voltage of the MTJ memory element and the reference voltage (V_{ref}). In addition, manufacturing yield of memory devices that include the MTJ memory element may be improved as a result of compensating for process variations and manufacturing defects by adjusting the reference resistance of the tunable reference circuit **300**. Adjusting a specific reference pair based on an optimizing algorithm will improve overall sensing margin for all MTJ elements in a memory device and also improve sensing margin for particular MTJ memory elements in the memory device. Such improvements in sensing margin may improve manufacturing yield of MRAM devices.

Although FIG. 3 illustrates three reference pairs **250**, **252**, **254**, the tunable reference circuit **300** may include greater than or less than three reference pairs. In addition, although a single pair of spare reference pair **302** is illustrated, more than one spare reference pairs may be configured to be coupled to the first, second, and nth reference pairs **250**, **252**, **254**.

Referring to FIG. 4, a particular illustrative embodiment of a tunable reference circuit is depicted and generally designated **400**. The tunable reference circuit **400** may provide a reference voltage (V_{ref}) that is based on a reference resistance of the tunable reference circuit **400** for use in determining a digital value corresponding to an output voltage of a memory element. The tunable reference circuit **400** may include the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and a reference block **402**. The first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may be coupled together in parallel. The reference block **402** may be tied in parallel to the first reference pair **250**, to the second reference pair **252**, and to the nth reference pair **254**. In a particular embodiment, the reference resistance of the tunable reference circuit **400** may be adjusted by adjusting a reference resistance of one or more of the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and the reference block **402**.

In a particular embodiment, the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may correspond to the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** of FIG. 2 and FIG. 3 and may operate as described with respect to FIG. 2 and FIG. 3. In a particular embodiment, each of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** may include a respective first MTJ element having a low resistance (R_p) in a parallel state) and a respective second MTJ element having a high resistance (R_{ap}) (e.g., in an anti-parallel state).

In a particular embodiment, the reference resistance of the tunable reference circuit **400** may be adjusted by adjusting a reference resistance of the reference block **402**. The reference block **402** may include an adjustable resistor network **404** that is configured to receive a resistance control signal (RCTL). The resistance of the adjustable resistor network **404** may be

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adjusted by adjusting the resistance control signal (RCTL). The reference block **402** may be configured to receive current via the reference bit line **266** or via the reference source line **264**. To enable a current to pass through the adjustable resistor network **404**, a reference source line control signal (CTLx) may be provided to a gate terminal of a transistor **406**.

During operation, the reference resistance of the tunable reference circuit **400** may be adjusted by adjusting the resistance of one or more of the first reference pair **250**, the second reference pair **252**, the nth reference pair **254**, and the reference block **402**. To illustrate, the resistance of the reference block **402** may be adjusted to increase or decrease the reference resistance of the tunable reference circuit **400**. The resistance of the reference block **402** may be adjusted by adjusting the resistance control signal (RCTL) to increase or decrease the resistance of the adjustable resistor network **404**.

Following the adjustment of the reference resistance of the tunable reference circuit **400**, the reference voltage (Vref) corresponding to the reference resistance of the tunable reference circuit **400** may be used to determine a digital value corresponding to an output voltage of an MTJ memory element, as described with respect to FIG. 2 and FIG. 3.

By adjusting the resistance of the reference block **402**, the reference resistance of the tunable reference circuit **400** may be adjusted. The reference voltage (Vref) may be correspondingly adjusted higher or lower as a result of adjusting the reference resistance of the tunable reference circuit **400**. Adjustment of the reference voltage (Vref) may improve the reliability of a digital value corresponding to an output voltage of an MTJ memory element that is determined (sensed) based on the output voltage of the MTJ memory element and the reference voltage (Vref). In addition, manufacturing yield of memory devices that include the MTJ memory element may be improved as a result of compensating for process variations and manufacturing defects by adjusting the reference resistance of the tunable reference circuit **400**. Adjusting a specific reference pair based on an optimizing algorithm will improve overall sensing margin for all MTJ elements in a memory device and also improve sensing margin for particular MTJ memory elements in the memory device. Such improvements in sensing margin may improve manufacturing yield of MRAM devices.

Referring to FIG. 5, a particular illustrative embodiment of a system including a tunable reference circuit is depicted and generally designated **500**. The system **500** may be configured to determine (sense) a digital value corresponding to an output voltage (Vdout) of a memory element **504**.

The system **500** includes a tunable reference circuit **502**, the memory element **504**, a sensing device **508** (e.g., a sense amplifier), and a tuning circuit **510**. The tuning circuit **510** may be coupled to the tunable reference circuit **502** via a tuning line **512**. The tunable reference circuit **502** may be coupled to a first input of the sensing device **508** to provide the reference voltage (Vref) to the sensing device **508**. The memory element **504** may be coupled to a second input of the sensing device **508** to provide an output voltage (Vdout) to the sensing device **508**.

The tuning circuit **510** may adjust the reference resistance of the tunable reference circuit **502** as described with respect to FIGS. 1-4. For example, the tuning circuit **510** may adjust the reference resistance of the tunable reference circuit **502** to increase or decrease the reference resistance. The reference voltage (Vref) may be adjusted corresponding to the reference resistance adjustment. In a particular embodiment, the tunable reference circuit **502** may correspond to any of the tunable reference circuit **100** of FIG. 1, the tunable reference

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circuit **200** of FIG. 2, the tunable reference circuit **300** of FIG. 3, and the tunable reference circuit **400** of FIG. 4.

The memory element **504** may be configured to provide the output voltage (Vdout) corresponding to a digital value. For example, the memory element **504** may be programmed to have a first resistance (e.g., low resistance (Ra)) corresponding to a first digital value. Alternatively, the memory element **504** may be programmed to have a second resistance (e.g., a high resistance (Rap)) corresponding to a second digital value. The memory element **504** may be configured to provide the output voltage (Vdout) during a read operation. In a particular embodiment, the memory element **504** may be an MTJ memory element.

The sensing device **508** is configured to determine a digital value corresponding to the output voltage (Vdout) of the memory element **504**. The sensing device **508** may determine whether the output voltage (Vdout) corresponds to the first digital value or to the second digital value based on the reference voltage (Vref).

In a particular embodiment, the tuning circuit **510** or another circuit (not shown) may be configured to program the memory element **504** to have a first resistance that corresponds to the first digital value. The tuning circuit **510** or another circuit (not shown) may be configured to receive an output signal (rdata) of the sensing device **508** to determine (sense) whether the output signal (rdata) corresponds to the first digital value. If the output signal (rdata) fails to correspond to the first digital value, the tuning circuit **510** may adjust the reference resistance of the tunable reference circuit **502** to correspondingly adjust the reference voltage (Vref). The tuning circuit **510** may repeatedly adjust the reference resistance of the tunable reference circuit **502** until the output signal (rdata) correspond to the first digital value. The tuning of the tunable reference circuit **502** may also be performed based on the second digital value to find a reference resistance of the tunable reference circuit **502** that enables a reliable determination (sensing) of both the first digital value and the second digital value.

During operation, the tuning circuit **510** may tune the tunable reference circuit **502** to adjust the reference resistance of the tunable reference circuit **502**. Following the tuning of the tunable reference circuit **502**, a read operation may be performed on the memory element **504**. During the read operation, the sensing device **508** may determine whether the output voltage (Vdata) corresponds to the first digital value or to the second digital value.

By tuning the tunable reference circuit **502** to adjust the reference resistance of the tunable reference circuit **502**, the reference voltage (Vref) is correspondingly adjusted. Adjustment of the reference voltage (Vref) may improve the reliability of the digital value that is determined (sensed) to correspond to the output voltage (Vdata) of the memory element. In addition, manufacturing yield of memory devices that include the memory element **504** may be improved as a result of compensating for process variations and manufacturing defects by adjusting the reference resistance of the tunable reference circuit **502**.

Although FIG. 5 illustrates one memory element **504** coupled to the second input of the sensing device **508**, the system **500** may include more than one memory element that may be selectively coupled to the second input of the sensing device **508**.

Referring to FIG. 6, a particular illustrative embodiment of a method of tuning a tunable reference circuit is illustrated. The method **600** includes selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel, at **602**. For example, the first reference pair **102** and the

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second reference pair **104** of FIG. **1** are tied together in parallel. The first path **106** of the first reference pair **102** of FIG. **1** may be selected. Similarly, the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** of FIG. **2** are tied together in parallel. The first path **260** of the first reference pair **250** of FIG. **2** may be selected by asserting the first control signal (CNTL**11**) of FIG. **2**. Each of the reference pairs may include a first path that includes a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element. For example, the first reference pair **102** of FIG. **1** includes the first path **106** that includes the first MTJ element **110**. The first reference pair **102** of FIG. **1** also includes the second path **108** that includes the second MTJ element **112**. The second reference pair **104** of FIG. **1** includes the first path **114** that includes the first MTJ element **118**. The second reference pair **104** of FIG. **1** also includes the second path **116** that includes the second MTJ element **120**. Similarly, each of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254** of FIG. **2** include a first path and a second path that include a corresponding MTJ element.

The method **600** further includes applying current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair, at **604**. For example, the current may be applied to the first path **106** of the first reference pair **102** of FIG. **1**. Similarly, the current may be applied to the first path **260** of the first reference pair **250** of FIG. **2**. A reference resistance of the tunable reference circuit may be based on a resistance of each reference pair of the plurality of reference pairs. For example, the reference resistance of the tunable reference circuit **100** of FIG. **1** may be based on the resistance of each of the first reference pair **102** and the second reference pair **104**. Similarly, the reference resistance of the tunable reference circuit **200** of FIG. **2** may be based on the resistance of each of the first reference pair **250**, the second reference pair **252**, and the nth reference pair **254**. The plurality of reference pairs may include a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state. The first number and the second number may be different. For example, the number of the MTJ elements **110**, **112**, **118**, **120** of FIG. **1** that are in the first state (e.g., a parallel state) may be different from the number of the MTJ elements **110**, **112**, **118**, **120** that are in the second state e.g., an anti-parallel state).

The method **600** of FIG. **6** may be implemented by an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA) device, a processing unit such as a central processing unit (CPU), a digital signal processor (DSP), a controller, another hardware device, a firmware device, or any combination thereof. As an example, the method of FIG. **6** can be performed by or in response to signals or commands from a processor that executes instructions, as described with respect to FIG. **7**.

Referring to FIG. **7**, a block diagram of a particular illustrative embodiment of a wireless communication device is depicted and generally designated **700**. The wireless communication device **700** includes a processor unit **710**, such as a digital signal processor (DSP), coupled to a memory **732**. The wireless communication device **700** may include a memory with a tunable reference circuit **764**. In an illustrative embodiment, the memory with the tunable reference circuit **764** may correspond to the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the tunable reference circuit **502** of FIG. **5**, or may operate according to the method of FIG. **6**, or any combination thereof.

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The memory **732** may be a non-transitory computer readable medium storing computer-executable instructions **746** that are executable by the processor unit **710** (e.g. a computer) to cause the processor unit **710** to select a path of a first reference pair of a plurality of reference pairs tied together in parallel. For example, the tuning instructions **746** may include instructions to select a path of a first reference pair of a plurality of reference pairs that are inside the memory with a tunable reference circuit **764** and tied together in parallel. Each of the reference pairs may include a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element. Additionally, the computer-executable instructions **746** may include instructions that are executable by the processor unit **710** to cause the processor unit **710** to apply current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair. For example, the tuning instructions **746** may include instructions to apply current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair that is inside the memory with a tunable reference circuit **764**. A reference resistance of the tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs. The plurality of reference pairs may include a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state. The first number and the second number may be different.

FIG. **7** also shows a display controller **726** that is coupled to the processor unit **710** and to a display **728**. A coder/decoder (CODEC) **734** can also be coupled to the processor unit **710**. A speaker **736** and a microphone **738** can be coupled to the CODEC **734**.

FIG. **7** indicates that a wireless controller **740** can be coupled to the processor unit **710** and to a wireless antenna **742**. In a particular embodiment, the processor unit **710**, the memory with the tunable reference circuit **764**, the display controller **726**, the memory **732**, the CODEC **734**, and the wireless controller **740** are included in a system-in-package or system-on-chip device **722**. In a particular embodiment, an input device **730** and a power supply **744** are coupled to the system-on-chip device **722**. Moreover, in a particular embodiment, as illustrated in FIG. **7**, the display **728**, the input device **730**, the speaker **736**, the microphone **738**, the wireless antenna **742**, and the power supply **744** are external to the system-on-chip device **722**. However, each of the display **728**, the input device **730**, the speaker **736**, the microphone **738**, the wireless antenna **742**, and the power supply **744** can be coupled to a component of the system-on-chip device **722**, such as an interface or a controller.

In a particular embodiment, a tuning circuit **768** may be coupled to the processor unit **710**. The tuning circuit **768** and the processor unit **710** may operate to adjust a reference resistance of the tunable reference circuit inside the memory with a tunable reference circuit **764**. In a particular embodiment, the tuning circuit **768** may be used in conjunction with the tuning instructions **746**. Alternatively, the tuning circuit **768** may operate independently of the tuning instructions **746** or with a memory that does not include tuning instructions.

While FIG. **7** illustrates a particular embodiment of a wireless device **700**, one or more memories (e.g., the memory with the tunable reference circuit **764**) may be integrated in other electronic devices including a set top box, a music player, a video player, an entertainment unit, a navigation device, a communications device, a personal digital assistant (PDA), a fixed location data unit, and a computer.

In conjunction with the described embodiments, a system is disclosed that may include means for selecting a path of a

first reference pair of a plurality of reference pairs tied together in parallel, each of the reference pairs including a first path including a first magnetic tunnel junction (NTH) element and a second path including a second. MTJ element. For example, the means for selecting a path may include the transistors **230**, **232**, **242**, **244**, **246**, and **248** of FIG. **2**, the transistors **230**, **232**, **242**, **244**, **246**, **248**, **308**, and **310** of FIG. **3**, the transistors **230**, **232**, **242**, **244**, **246**, and **248** of FIG. **4**, one or more other devices or circuits configured to select a path, or any combination thereof. The system may also include means for applying current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair, where a reference resistance of the tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs, where the plurality of reference pairs includes a first number of MTJ elements that are in a first state and a second number of elements that are in a second state, and where the first number and the second number are different. The means for applying current to the selected path may include the reference bit line **266** of FIG. **2**, reference source line **264** of FIG. **2**, the reference bit line **266** of FIG. **3**, reference source line **264** of FIG. **4**, the reference bit line **266** of FIG. **4**, reference source line **264** of FIG. **4**, one or more other devices or circuits configured to apply current to the selected path, or any combination thereof.

The foregoing disclosed devices and functionalities may be designed and configured into computer files (e.g., RTL, GDSII, GERBER, etc.) stored on computer readable media. Some or all such files may be provided to fabrication handlers who fabricate devices based on such files. Resulting products include semiconductor wafers that are then cut into semiconductor die and packaged into a semiconductor chip. The chips are then employed in devices described above. FIG. **8** depicts a particular illustrative embodiment of an electronic device manufacturing process **800**.

Physical device information **802** is received at the manufacturing process **800**, such as at a research computer **806**. The physical device information **802** may include design information representing at least one physical property of a semiconductor device, such as a semiconductor device that includes the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, the system of FIG. **5**, or any combination thereof. For example, the physical device information **802** may include physical parameters, material characteristics, and structure information that is entered via a user interface **804** coupled to the research computer **806**. The research computer **806** includes a processor **808**, such as one or more processing cores, coupled to a computer readable medium such as a memory **810**. The memory **810** may store computer readable instructions that are executable to cause the processor **808** to transform the physical device information **802** to comply with a file format and to generate a library file **812**.

In a particular embodiment, the library file **812** includes at least one data file including the transformed design information. For example, the library file **812** may include a library of semiconductor devices including a device that includes the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof, that is provided for use with an electronic design automation (EDA) tool **820**.

The library file **812** may be used in conjunction with the EDA tool **820** at a design computer **814** including a processor **816**, such as one or more processing cores, coupled to a memory **818**. The EDA tool **820** may be stored as processor executable instructions at the memory **818** to enable a user of

the design computer **814** to design a circuit including the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof, of the library file **812**. For example, a user of the design computer **814** may enter circuit design information **822** via a user interface **824** coupled to the design computer **814**. The circuit design information **822** may include design information representing at least one physical property of a semiconductor device, such as a device including the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof. To illustrate, the circuit design property may include identification of particular circuits and relationships to other elements in a circuit design, positioning information, feature size information, interconnection information, or other information representing a physical property of a semiconductor device.

The design computer **814** may be configured to transform the design information, including the circuit design information **822**, to comply with a file format. To illustrate, the file format may include a database binary file format representing planar geometric shapes, text labels, and other information about a circuit layout in a hierarchical format, such as a Graphic Data System (GDSII) file format. The design computer **814** may be configured to generate a data file including the transformed design information, such as a GDSII file **826** that includes information describing the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof, in addition to other circuits or information. To illustrate, the data file may include information corresponding to a system-on-chip (SOC) that includes the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, and that also includes additional electronic circuits and components within the SOC.

The GDSII file **826** may be received at a fabrication process **828** to manufacture the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof, according to transformed information in the GDSII file **826**. For example, a device manufacture process may include providing the GDSII file **826** to a mask manufacturer **830** to create one or more masks, such as masks to be used with photolithography processing, illustrated as a representative mask **832**. The mask **832** may be used during the fabrication process to generate one or more wafers **834**, which may be tested and separated into dies, such as a representative die **836**. The die **836** includes circuits that include the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof.

The die **836** may be provided to a packaging process **838** where the die **836** is incorporated into a representative package **840**. For example, the package **840** may include the single die **836** or multiple dies, such as a system-in-package (SiP) arrangement. The package **840** may be configured to conform to one or more standards or specifications, such as Joint Electron Device Engineering Council (JEDEC) standards.

Information regarding the package **840** may be distributed, to various product designers, such as via a component library stored at a computer **846**. The computer **846** may include a processor **848**, such as one or more processing cores, coupled to a memory **850**. A printed circuit board (PCB) tool may be stored as processor executable instructions at the memory **850** to process PCB design information **842** received from a user of the computer **846** via user interface **844**. The PCB design

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information **842** may include physical positioning information of a packaged semiconductor device on a circuit board, the packaged semiconductor device corresponding to the package **840** including the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, the system of FIG. **5**, or any combination thereof.

The computer **846** may be configured to transform the PCB design information **842** to generate a data file, such as a GERBER file **852**, with data that includes physical positioning information of a packaged semiconductor device on a circuit board, as well as layout of electrical connections such as traces and vias, where the packaged semiconductor device corresponds to the package **840** including the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof. In other embodiments, the data file generated by the transformed PCB design information may have a format other than a GERBER format.

The GERBER file **852** may be received at a board assembly process **854** and used to create PCBs, such as a representative PCB **856** manufactured in accordance with the design information stored within the GERBER file **852**. For example, the GERBER file **852** may be uploaded to one or more machines to perform various steps of a PCB production process. The PCB **856** may be populated with electronic components including the package **840** to form a representative printed circuit assembly (PCA) **858**.

The PCA **858** may be received at a product manufacture process **860** and integrated into one or more electronic devices, such as a first representative electronic device **862** and a second representative electronic device **864**. As an illustrative, non-limiting example, the first representative electronic device **862**, the second representative electronic device **864**, or both, may be selected from the group of a set top box, a music player, a video player, an entertainment unit, a navigation device, a communications device, a personal digital assistant (PDA), a fixed location data unit, and a computer, into which the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof is integrated. As another illustrative, non-limiting example, one or more of the electronic devices **862** and **864** may be remote units such as mobile phones, hand-held personal communication systems (PCS) units, portable data units such as personal data assistants, global positioning system (GPS) enabled devices, navigation devices, fixed location data units such as meter reading equipment, or any other device that stores or retrieves data or computer instructions, or any combination thereof. Although FIG. **8** illustrates remote units according to teachings of the disclosure, the disclosure is not limited to these illustrated units. Embodiments of the disclosure may be suitably employed in any device that includes active integrated circuitry including memory and on-chip circuitry.

A device that includes the circuit **100** of FIG. **1**, the circuit **200** of FIG. **2**, the circuit **300** of FIG. **3**, the circuit **400** of FIG. **4**, and the system of FIG. **5**, or any combination thereof, may be fabricated, processed, and incorporated into an electronic device, as described in the illustrative process **800**. One or more aspects of the embodiments disclosed with respect to FIGS. **1-7** may be included at various processing stages, such as within the library file **812**, the GDSII file **826**, and the GERBER file **852**, as well as stored at the memory **810** of the research computer **806**, the memory **818** of the design computer **814**, the memory **850** of the computer **846**, the memory of one or more other computers or processors (not shown) used at the various stages, such as at the board assembly process **854**, and also incorporated into one or more other

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physical embodiments such as the mask **832**, the die **836**, the package **840**, the PCA **858**, other products such as prototype circuits or devices (not shown), or any combination thereof. Although various representative stages of production from a physical device design to a final product are depicted, in other embodiments fewer stages may be used or additional stages may be included. Similarly, the process **800** may be performed by a single entity or by one or more entities performing various stages of the process **800**.

Those of skill would further appreciate that the various illustrative logical blocks, configurations, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic hardware, computer software executed by a processor, or combinations of both. Various illustrative components, blocks, configurations, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or processor executable instructions depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in random access memory (RAM), flash memory, read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), registers, hard disk, a removable disk, a compact disc read-only memory (CD-ROM), or any other form of non-transient storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an application-specific integrated circuit (ASIC). The ASIC may reside in a computing device or a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a computing device or user terminal.

The previous description of the disclosed embodiments is provided to enable a person skilled in the art to make or use the disclosed embodiments. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the principles defined herein may be applied to other embodiments without departing from the scope of the disclosure. Thus, the present disclosure is not intended to be limited to the embodiments shown herein but is to be accorded, the widest scope possible consistent with the principles and novel features as defined by the following claims.

What is claimed is:

1. A method of tuning a tunable reference circuit, the method comprising:

selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel, each of the reference pairs including a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element; and

applying current to the selected path to set an MTJ resistance of an MTJ element in the selected path of the first reference pair, wherein a reference resistance of the tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs, wherein

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the plurality of reference pairs includes a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state, and wherein the first number and the second number are different.

2. The method of claim 1, further comprising comparing an output voltage of a memory element to a reference voltage of the tunable reference circuit to determine a digital value corresponding to the output voltage of the memory element, wherein the reference voltage of the tunable reference circuit is based on the reference resistance of the tunable reference circuit.

3. The method of claim 1, wherein the reference resistance of the tunable reference circuit is an average of the resistance of each reference pair of the plurality of reference pairs and wherein the first state corresponds to a parallel-state and the second state corresponds to an anti-parallel state.

4. The method of claim 1, wherein a first resistance of the MTJ element in the selected path of the first reference pair corresponds to the first state of the MTJ element, wherein a second resistance of the MTJ element in the selected path of the first reference pair corresponds to the second state of the MTJ element, and wherein the second resistance is greater than the first resistance.

5. The method of claim 1, wherein the path of the first reference pair of the plurality of reference pairs is selected based on information on spatial location of the first and the second MTJ elements in each reference pair and based on variations in the resistances of the first and the second MTJ elements in each reference pair.

6. The method of claim 1, further comprising asserting at least one control signal to enable adequate current to flow through the MTJ element in the selected path of the first reference pair.

7. The method of claim 6, wherein the first path includes a first transistor, wherein the second path includes a second transistor, wherein a first control signal is provided to a gate terminal of the first transistor, and wherein a second control signal is provided to a gate terminal of the second transistor.

8. A circuit comprising:

a first reference pair including a first path and a second path, the first path including a first magnetic tunnel junction (MTJ) element and the second path including a second MTJ element; and

a second reference pair including a third path and a fourth path, the third path including a third MTJ element and the fourth path including a fourth MTJ element,

wherein the first reference pair and the second reference pair are tied together in parallel, wherein a reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements, wherein the reference resistance of the circuit is adjustable by adjusting a resistance of one of the first and second MTJ elements, wherein a first number of the first, the second, the third, and the fourth MTJ elements are in a first state, wherein a second number of the first, the second, the third, and the fourth MTJ elements are in a second state, and wherein the first number and the second number are different.

9. The circuit of claim 8, wherein an output voltage of a memory element is compared to a reference voltage corresponding to the reference resistance of the circuit to determine a digital value corresponding to the output voltage of the memory element.

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10. A circuit comprising:

a first reference pair including a first path and a second path, the first path including a first magnetic tunnel junction (MTJ) element and the second path including a second MTJ element; and

a second reference pair including a third path and a fourth path, the third path including a third MTJ element and the fourth path including a fourth MTJ element, wherein the first reference pair and the second reference pair are coupled together in parallel, wherein a reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements, and wherein the reference resistance of the circuit is adjustable by adjusting a resistance of one of the first and second MTJ elements; and

a spare reference pair that is coupled in parallel to the first reference pair and to the second reference pair, the spare reference pair including a first spare MTJ element and a second spare MTJ element, wherein the reference resistance of the circuit is adjustable by adjusting a resistance of the first spare MTJ element, and wherein an output voltage of a memory element is compared to a reference voltage corresponding to the reference resistance of the circuit to determine a digital value corresponding to the output voltage of the memory element.

11. The circuit of claim 10, wherein the spare reference pair is included in an array of reference pairs, the array of reference pairs including the first reference pair and the second reference pair.

12. The circuit of claim 10, wherein the spare reference pair is external to an array of reference pairs, the array of reference pairs including the first reference pair and the second reference pair.

13. A circuit comprising:

a first reference pair including a first path and a second path, the first path including a first magnetic tunnel junction (MTJ) element and the second path including a second MTJ element; and

a second reference pair including a third path and a fourth path, the third path including a third MTJ element and the fourth path including a fourth MTJ element, wherein the first reference pair and the second reference pair are coupled together in parallel, wherein a reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements, and wherein the reference resistance of the circuit is adjustable by adjusting a resistance of one of the first and second MTJ elements; and

a reference block that is coupled in parallel to the first reference pair and to the second reference pair, wherein the reference block includes an adjustable resistor network, wherein the reference resistance of the circuit is adjustable by adjusting a resistance of the adjustable resistor network.

14. The circuit of claim 8, further comprising a memory path including a memory element that is tied in parallel to the first reference pair and to the second reference pair.

15. The circuit of claim 8, wherein the reference resistance of the circuit is adjusted after a self-test is performed on the circuit to determine initial resistance of the circuit.

16. The circuit of claim 8, wherein the reference resistance of the circuit is adjusted after a test is performed on the circuit to determine initial resistance of the circuit.

17. The circuit of claim 8, wherein the first path includes a first transistor, wherein a first control input is coupled to a gate terminal of the first transistor, wherein the second path includes a second transistor, wherein a second control input is

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coupled to a gate terminal of the second transistor, and wherein the first control input is different from the second control input.

18. The circuit of claim 8 integrated in at least one semiconductor die.

19. The circuit of claim 8, wherein the resistance of the one of the first reference pair and the second reference pair is adjusted based on spatial location information of the first reference pair and the second reference pair and based on variations in resistances of the first, second, third, and fourth MTJ elements.

20. The circuit of claim 8, further comprising a device selected from the group consisting of a set top box, a music player, a video player, an entertainment unit, a navigation device, a communications device, a personal digital assistant (PDA), a fixed location data unit, and a computer, into which the first reference pair and the second reference pair are integrated.

21. An apparatus comprising:

means for selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel, each of the reference pairs including a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element; and

means for applying current to the selected path to set a resistance of an MTJ element in the selected path of the first reference pair, wherein a reference resistance of the apparatus is based on a resistance of each reference pair of the plurality of reference pairs, wherein the plurality of reference pairs includes a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state, and wherein the first number and the second number are different.

22. The apparatus of claim 21, further comprising means for comparing an output voltage of a memory element to the reference voltage of the tunable reference circuit to determine the state of the memory element.

23. The apparatus of claim 21, wherein the reference resistance of the tunable reference circuit is an average of the resistance of each reference pair of the plurality of reference pairs and wherein the first state corresponds to a parallel-state and the second state corresponds to an anti-parallel state.

24. The apparatus of claim 21, wherein a first resistance of the MTJ element in the selected path of the first reference pair corresponds to the first state of the MTJ element, wherein a second resistance of the MTJ element in the selected path of the first reference pair corresponds to the second state of the MTJ element, and wherein the second resistance is greater than the first resistance.

25. The apparatus of claim 21, wherein the path of the first reference pair of the plurality of reference pairs is selected based on information on spatial location of the first and the second MTJ elements in each reference pair and based on variations in the resistances of the first and the second MTJ elements in each reference pair.

26. A method comprising:

a step for selecting a path of a first reference pair of a plurality of reference pairs tied together in parallel, each of the reference pairs including a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element; and

a step for applying current to the selected path to set a resistance of an MTJ element in the selected path of the first reference pair, wherein a reference resistance of a tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs, wherein the plurality of reference pairs includes a first number of

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MTJ elements that are in a first state and a second number of MTJ elements that are in a second state, and wherein the first number and the second number are different.

27. The method of claim 26, wherein selecting the first reference pair of the plurality of reference pairs is performed at a processor integrated into an electronic device.

28. The method of claim 26, wherein the path of the first reference pair of the plurality of reference pairs is selected based on information on spatial location of the first and the second MTJ elements in each reference pair and based on variations in the resistances of the first and the second MTJ elements in each reference pair.

29. A non-transitory computer readable tangible medium storing instructions executable by a computer, the instructions comprising:

instructions that are executable by the computer to select a path of a first reference pair of a plurality of reference pairs tied together in parallel, each of the reference pairs including a first path including a first magnetic tunnel junction (MTJ) element and a second path including a second MTJ element; and

instructions that are executable by the computer to apply current to the selected path to set a resistance of an MTJ element in the selected path of the first reference pair, wherein a reference resistance of a tunable reference circuit is based on a resistance of each reference pair of the plurality of reference pairs, wherein the plurality of reference pairs includes a first number of MTJ elements that are in a first state and a second number of MTJ elements that are in a second state, and wherein the first number and the second number are different.

30. The non-transitory computer readable tangible medium of claim 29, further comprising instructions that are executable by the computer to compare a resistance of a memory element to the reference resistance of the tunable reference circuit to determine the state of the memory element.

31. The non-transitory computer readable tangible medium of claim 29, wherein the path of the first reference pair of the plurality of reference pairs is selected based on information on spatial location of the first and the second MTJ elements in each reference pair and based on variations in the resistances of the first and the second MTJ elements in each reference pair.

32. A method comprising:

receiving a data file comprising design information corresponding to a semiconductor device; and

fabricating the semiconductor device according to the design information, wherein the semiconductor device comprises:

a first reference pair including a first path and a second path, the first path including a first magnetic tunnel junction (MTJ) element and the second path including a second MTJ element; and

a second reference pair including a third path and a fourth path, the third path including a third MTJ element and the fourth path including a fourth MTJ element,

wherein the first reference pair and the second reference pair are tied together in parallel, wherein a reference resistance of the circuit is based on a resistance of each of the first, second, third, and fourth MTJ elements, and wherein the reference resistance of the circuit is adjustable by adjusting a resistance of one of the first and second MTJ elements, wherein a first number of the first, the second, the third, and the

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fourth MTJ elements are in a first state, wherein a second number of the first, the second, the third, and the fourth MTJ elements are in a second state, and wherein the first number and the second number are different.

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33. The method of claim 32, wherein the data file has a GDSII format.

34. The method of claim 32, wherein the data file has a GERBER format.

35. The method of claim 32, wherein the resistance of the one of the first reference pair and the second reference pair is adjusted based on spatial location information of the first reference pair and the second reference pair and based on variations in resistances of the first, second, third, and fourth MTJ elements.

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36. The method of claim 2, further comprising adjusting the reference resistance of the tunable reference circuit by adjusting a resistance of a first spare MTJ element of a spare reference pair that includes the first spare MTJ element and a second spare MTJ element, and wherein the spare reference pair is coupled in parallel to the first reference pair and to a second reference pair.

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